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THE THEORETICAL AND METHODOLOGICAL FOUNDATIONS FOR FORMING A SYSTEM OF BALANCES IN SUSTAINABLE TERRITORIAL DEVELOPMENT DURING THE GREEN ECONOMY TRANSITION

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Bozhydarnik Z. V. The Theoretical and Methodological Foundations for Forming a System of Balances in Sustainable Territorial Development During the Green Economy Transition

The aim of the study is to advance the theoretical and methodological foundations for the formation and quantitative assessment of a system of sustainable territorial development balances in the context of the transition to a green economy. Sustainable development is proposed to be viewed as the outcome of the simultaneous coordination of four interrelated balances: «economic growth – environmental security», «economic efficiency – social justice», «current consumption – interests of future generations», and «economic openness – economic security». The methodological approach distinguishes between the level of simultaneous achievement of paired objectives and the degree of their coherence; adjusted indices are also proposed for comprehensive assessment. The overall result is assessed in parallel using arithmetic and geometric indices, while the difference between them is proposed as a compensation gap that reflects the extent to which weaker partial balances are offset by stronger ones. The methodology was tested using 2021 statistical data for 24 regions of Ukraine and the city of Kyiv, based on eight primary indicators. The robustness analysis confirmed the overall reliability of the proposed approach while also demonstrating the need to account for the structural characteristics of individual regions when interpreting integrated assessments. The proposed model makes it possible not only to rank territories, but also to identify structural imbalances, assess compensation effects, and determine priorities for regional green transformation policy. The practical significance of the results lies in the potential application of the system of balances to diagnose territorial disparities, identify problematic components of development, and substantiate priorities for regional green transformation policy.

Keywords: *sustainable territorial development; green economy; economic growth; environmental security; social justice; intergenerational equity; economic security; integral index; system of balances.*
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Bozhydarnik Zoriana V. *– D. Sc. (Economics), Professor, Professor of the Department of Law and Economic and Financial Security, Academy of Recreation Technologies and Law (2 Karbysheva Str., Lutsk, 43023, Ukraine)*
E-mail: *z11w11b@gmail.com*
ORCID: *https://orcid.org/0000-0002-3676-4147*

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Божидарнік З. В. Теоретико-методичні засади формування балансів сталого розвитку територій в умовах переходу до зеленої економіки

Метою дослідження є розвиток теоретико-методичних засад формування та кількісного оцінювання системи балансів сталого розвитку територій в умовах переходу до зеленої економіки. Запропоновано розглядати сталий розвиток як результат одночасного узгодження чотирьох взаємопов'язаних балансів: «економічне зростання – екологічна безпека», «економічна ефективність – соціальна справедливість», «поточне споживання – інтереси майбутніх поколінь» та «економічна відкритість – економічна безпека». Методичний підхід розмежовує рівень одночасного досягнення парних цілей та ступінь їх узгодженості; для комплексної оцінки запропоновано також скориговані індекси. Інтегральний результат визначається паралельно за арифметичним індексом і геометричним індексом, а різницю між ними запропоновано використовувати як компенсаційний розрив, що характеризує міру компенсації слабких часткових балансів сильнішими. Методику апробовано на статистичних даних 24 областей України та м. Києва за 2021 рік із використанням восьми первинних показників. Перевірка стійкості результатів підтвердила загальну надійність запропонованого підходу та водночас показала необхідність урахування структурних особливостей регіонів під час інтерпретації інтегральних оцінок. Запропонована модель дає змогу не лише ранжувати території, а й виявляти структурні дисбаланси, оцінювати компенсаційний ефект і визначати пріоритети регіональної політики зеленої трансформації. Практичне значення результатів полягає в можливості використання системи балансів для діагностики територіальних диспропорцій, визначення проблемних складових розвитку та обґрунтування пріоритетів регіональної політики зеленої трансформації.

Ключові слова: *сталий розвиток територій; зелена економіка; економічне зростання; екологічна безпека; соціальна справедливість; міжпоколінна справедливість; економічна безпека; інтегральний індекс; система балансів.*
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Божидарнік Зоряна Вікторівна *– доктор економічних наук, професор, професор кафедри права та економіко-фінансової безпеки, Академія рекреаційних технологій та права (вул. Карбишева, 2, Луцьк, 43023, Україна)*
E-mail: *z11w11b@gmail.com*
ORCID: *https://orcid.org/0000-0002-3676-4147*

In contemporary academic discourse, the green economy concept is regarded as one of the key models for ensuring sustainable development by combining economic growth, environmental security, and social justice. A regional policy that maximizes one outcome may simultaneously worsen another: accelerated production increases pressure on natural capital; stronger social protection requires additional resources; current consumption may reduce opportunities for future generations; and high economic openness increases exposure to adverse external impacts. Accordingly, a key characteristic of sustainable territorial development is the achievement of a balance among competing objectives of societal development.

The difficulty of achieving and maintaining balanced territorial development over the long term stems from insufficient consideration of the internal contradictions of socioeconomic and environmental development, as well as from the limited mathematical tools available for their comprehensive assessment. Therefore, the key task is not to maximize an individual indicator but to find a sustainable relationship among competing objectives that determines the balance of territorial development.

The scientific problem lies in the absence of a holistic model that would combine the main trade-offs of territorial development within a single system of quantitative analysis. This necessitates the formation of a system of sustainable development balances and mathematical tools for their assessment.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

In contemporary academic literature, sustainable territorial development is examined at the intersection of research on economic growth, environmental sustainability, social inclusion, intergenerational equity, and economic security. The theoretical foundations of modern approaches were shaped by H. Daly's concept of the steady-state economy, A. Sen's capability approach to development, J. Rawls's theory of justice, R. Solow's and J. Hartwick's propositions concerning the intergenerational allocation of natural capital, and D. Rodrik's studies of the contradictions among economic globalization, national policy, and economic resilience [3; 12; 13; 22–24]. Pareto theory [26] and modern multiobjective optimization [25] are methodologically important for studying trade-offs among development objectives. Pareto optimality [26] and contemporary approaches to multiobjective optimization [25] make it possible to analyze situations in which improving one criterion may worsen another. However, these tools are used primarily to find optimal solutions to specific problems, whereas territorial analysis requires a comprehensive indicator system capable of simultaneously showing the state of each key trade-off and its impact on the overall sustainability of territorial development.

Contemporary studies of regional sustainable development extend this approach toward multidimensional assessment of the coordination and balance of territorial systems. In particular, methods have been proposed for comprehensively measuring the level of coordinated regional development with regard to economic, social, and environmental parameters [1]. At the same time, recent empirical studies confirm a persistent contradiction between the objectives of socioeconomic territorial development and environmental sustainability, which requires their joint assessment within regional policy [2].

In international research, sustainable development is increasingly viewed not as the attainment of isolated target indicators but as a problem of coordinating economic, social, and environmental outcomes. A substantial body of research has developed around the Sustainable Development Goals (SDGs), OECD green growth indicators, environmental and social indicators, and approaches to assessing the resilience of economic systems. At the same time, these systems primarily provide a multidimensional information base for monitoring, ranking comparisons, and assessing progress in individual areas.

A major strand of contemporary international research concerns the transition from the traditional economic growth model to a green economy and green transformation. The OECD considers green growth through a system of indicators combining economic outcomes, resource productivity, natural assets, and environmental quality of life [8]. The IEA emphasizes structural changes in the energy sector, the reallocation of investment flows toward clean energy technologies, the development of grid and storage infrastructure [4; 5], and long-term changes in the structure of the global energy balance [11]. Improving energy efficiency is an important component of green transformation, simultaneously reducing the energy intensity of production and emissions, increasing competitiveness, and decreasing dependence on imported energy resources [6]. At the same time, recent studies of green transformation show that its outcomes may be uneven across territories and social groups, increasing the importance of the fair distribution of costs and benefits.

At the territorial level, coordinating economic dynamics with environmental constraints is of particular importance. Under the green economy concept, economic growth should be accompanied by lower resource intensity, reduced adverse environmental impacts, and preservation of natural capital. Interna-

tional studies and analytical materials from the OECD and IEA show that green transformation simultaneously creates economic opportunities and generates new structural, investment, and social risks. Assessing the effectiveness of green transformation therefore requires consideration not only of positive effects but also of potential losses and constraints. Contemporary approaches to climate and green transformation increasingly seek to align it not only with environmental objectives but also with economic and social resilience, as reflected, in particular, in the OECD Net Zero+ program [9].

A separate strand of international research on balanced territorial development concerns the suboptimal relationship between economic efficiency and social justice. Contemporary literature analyzes the effects of minimum wages, tax and social reforms, energy subsidies, and other public policy measures while simultaneously considering impacts on household income, employment, and economic activity. Studies of Spain's 2019 minimum-wage reform, for example, show the possibility of a positive effect on the income of low-paid workers occurring alongside a negative effect on the employment of particular groups [14; 15]. A broader analysis of the relationship among the minimum wage, social justice, and economic efficiency presented in an analytical report by the French public expert body Conseil d'analyse économique (CAE) shows that the effect of this instrument depends on labor-market structure, wage levels, productivity, and the possibilities for targeted support of low-income groups [16]. OECD studies likewise emphasize that, after periods of crisis, the minimum wage can be an important instrument for supporting incomes, but its level should be set with due regard to effects on employment and labor demand [17]. A practical example of this contradiction is the 2024 debate over increasing the minimum wage in Türkiye, where the need to protect real household incomes amid high inflation was considered together with the risks of additional inflationary pressure, higher business costs, and weaker price stability [18]. A similar problem appears in energy-policy research, where social support for households may conflict with budgetary efficiency and environmental transformation objectives [19–21]. Thus, international literature has accumulated substantial empirical evidence on individual trade-offs among development objectives, but these compromises are generally analyzed as separate policy or sectoral cases.

Ukrainian scholars such as M. I. Dolishniy, V. S. Kravtsiv, B. M. Danylyshyn, B. V. Burkynskyi, L. H. Rudenko, Z. V. Herasymchuk, and others have made important contributions to research on regional aspects of sustainable development, its assessment, and the transition of regions to a green economy. Ukrainian studies of sustainable territorial development provide an important foundation for the further development of territorial assessment methodology. Specialists of the M. I. Dolishniy Institute of Regional Research of the NAS of Ukraine have made a significant contribution to studying the regional dimension of sustainable development. In particular, the study "Sustainable Development Goals for Ukraine: Regional Dimension" established an analytical basis for assessing regional potential to achieve the SDGs and monitored regional differentiation by socioeconomic and environmental indicators [27]. An important result of this strand of research is the adaptation of the global Sustainable Development Goals to Ukraine's national and regional specificities.

The Ukrainian academic school also devotes considerable attention to the greening of regional economies, rational use of natural resources, and the formation of green transformation mechanisms. In particular, studies by B. V. Burkynskyi, T. P. Halushkina, and other authors laid the methodological foundations for a regional "green" strategy by integrating balanced natural-resource use, environmental governance, and sustainable territorial development [28]. At the present stage, these approaches are being developed toward research on green transformation of regional economies, the circular economy, resource efficiency, and post-war green recovery.

The current stage of Ukrainian regional-development research is characterized by growing attention to green and digital transformation, environmental differentiation of territories, the circular economy, energy efficiency, institutional capacity, and post-war recovery. At the same time, the key issue is not the list of individual transformation areas but the methodological possibility of quantitatively assessing the coherence of competing sustainable-development objectives during transformational change.

Contemporary Ukrainian scholarship focuses primarily on individual components of sustainable development: regional economic efficiency, environmental security, social resilience, resource efficiency, green transformation, or spatial integration. Existing regional monitoring systems make it possible to determine the level of achievement of individual objectives and identify territorial disparities, but they do not provide an unambiguous answer as to how coherently the interrelated components of a territorial system are developing.

This problem becomes particularly important amid Ukraine's wartime and post-war transformations. Regional economies simultaneously face the need to restore production, support employment and house-

hold incomes, ensure energy and economic security, restore natural capital, and transition to a low-carbon development model. Future regional sustainable-development policy in Ukraine must take into account that improving one component may be accompanied by deterioration in another. For example, stimulating industrial production may increase economic activity but also environmental pressure; strengthening social support may improve social justice but create an additional fiscal burden; expanding foreign trade may increase regional economic openness but also deepen dependence on external markets and critical suppliers.

A synthesis of Ukrainian and international research makes it possible to identify three principal strands of scholarship: SDG, ESG, and other indicator systems for monitoring individual sustainability parameters; multidimensional indices and ranking methodologies; and studies of individual trade-offs among economic, social, environmental, intergenerational, and security objectives. A common limitation of these approaches for the purposes of this study is the insufficient formalization of the set of interrelated trade-offs within a unified model of territorial sustainable development. It is particularly important to account for the compensation effect, whereby a high level of one component of an integral index may conceal a critically low level of another.

Thus, the research gap lies in the absence of a methodologically coherent approach that simultaneously treats sustainable territorial development as a system of interrelated balances, identifies pairs of potentially conflicting objectives, quantitatively assesses both their level of achievement and coherence, aggregates partial results into an integral characteristic, and makes it possible to test the robustness of conclusions to normalization and weights. The proposed system of four balances is intended to fill this gap.

AIM, OBJECTIVES, AND RESEARCH HYPOTHESIS

The *aim* of the study is to develop theoretical and methodological foundations for forming and quantitatively assessing a system of sustainable territorial development balances in the transition to a green economy.

To achieve this purpose, the following objectives were set:

- to systematize the main contradictions among the economic, environmental, social, intergenerational, and security objectives of territorial development;
- to define four basic balances and a system of indicators for measuring them;
- to develop a procedure for normalizing indicators and determining weighting coefficients;
- to construct partial and integral balance models;
- to demonstrate the practical applicability of the proposed approach using empirical examples;
- to formulate practical recommendations for using the model in territorial-development management.

The research hypothesis is that the sustainability of territorial development is determined not by the maximum value of an individual economic, social, or environmental characteristic, but by the degree of coherence among competing objectives; therefore, a system of such trade-offs can be formalized through a set of normalized partial balances and reduced to an integral index.

MATERIALS AND METHODS

The methodology combines a systems approach, comparative analysis, synthesis of international and Ukrainian experience, indicator normalization methods, multi-criteria assessment, integral indexing, and scenario analysis. The information base for cross-country and comparative studies may include IEA data, the World Bank's World Development Indicators database [7], OECD and Eurostat statistical systems, while empirical testing for Ukrainian regions relies on official data from the State Statistics Service of Ukraine and other official statistical authorities.

To ensure comparability, primary indicators with different dimensions are converted to a dimensionless [0; 1] scale. Min-max normalization is used for a stimulant indicator:

$$z_i = (x_i - x_{\min})/(x_{\max} - x_{\min}). \quad (1)$$

For a destimulant indicator, formula (2) is used:

$$z_i = (x_{\max} - x_i)/(x_{\max} - x_{\min}). \quad (2)$$

The $x_{\min}$ and $x_{\max}$ boundaries should be determined using a common sample of territories and periods or normative/target values.

Weighting coefficients are proposed to be determined in three modes: *neutral* – equal weights; *expert* – weights obtained by the Analytic Hierarchy Process (AHP) with a consistency check; and *objective* – weights determined by the entropy method. Sensitivity analysis is additionally performed for policy scenario analysis.

For each balance j, the partial index is determined by formula (3):

$$B_j = \alpha_j X_j + \beta_j Y_j. \quad (3)$$

where X_j and Y_j are the normalized components of the balance; α_j and β_j are their weights; $\alpha_j + \beta_j = 1$.

The linear combination $B_j = \alpha_j X_j + \beta_j Y_j$ primarily characterizes the level of simultaneous achievement of

two objectives, but by itself does not measure the symmetry of their relationship. With equal weights, for example, the pairs (1; 0) and (0.5; 0.5) yield the same $B_j = 0.5$, although the second pair is substantially more coherent. The model should therefore formally distinguish between the level of objective achievement and the degree of balance between them.

To directly measure the internal mismatch within a pair, the imbalance coefficient $D_j = |X_j - Y_j|$, where $0 \le D_j \le 1$, and the corresponding coherence coefficient $C_j = 1 - D_j$ are introduced.

The closer C_j is to 1, the smaller the gap between the two components. Thus, B_j reflects the level of achievement of paired objectives, while C_j represents the degree of their coherence. When a single adjusted estimate is required, $B_j^* = B_j \cdot C_j$ can be used, simultaneously accounting for both the level and symmetry of objective achievement.

This distinction is fundamental to interpreting the term "balance": a high B_j with a low C_j indicates a high aggregate result generated by the dominance of one component, whereas simultaneously high B_j and C_j indicate a high and coherent level of achievement of both objectives.

The integral sustainable development index is determined by formula (4):

$$SD = \sum_j w_j B_j, \sum_j w_j = 1. \quad \textbf{(4)}$$

In the absence of substantiated priorities, the baseline option is $\alpha_j = \beta_j = 0.5$ and $w_j = 0.25$. These weights constitute a control scenario rather than a universally optimal solution.

A common comparison base is used for empirical testing: 24 regions of Ukraine and the city of Kyiv in 2021. The Autonomous Republic of Crimea and the city of Sevastopol are excluded because comparable official statistics are unavailable. Donetsk and Luhansk regions are included using officially published indicators compiled without the temporarily occupied territories; the same territorial-coverage principle is applied to all eight indicators.

RESEARCH RESULTS

System of Basic Sustainable Development Ba-lances

In scientific terms, balance means the coherence of interests, resources, development rates, and outcomes across different spheres of social activity. Based on a synthesis of theoretical approaches, four basic balances are identified:

- economic growth – environmental security;
- economic efficiency – social justice;
- current consumption – interests of future generations;
- economic openness – economic security.

According to formula (3), the normalized balance components are divided into benefit component *X* and resilience component *Y*. The system of basic sustainable territorial development balances and examples of indicators are summarized in *Tbl. 1*.

The indicators are proxy measures of the respective components. This applies particularly to the third and fourth balances, where full measurement of natural capital and economic security requires a broader data system.

Balance Between Economic Growth and Environmental Security

Its essence is to ensure economic growth without excessive depletion of natural resources and environmental degradation. In H. Daly's approach, the economic system is viewed as a subsystem of a finite biosphere; therefore, long-term growth cannot be assessed without taking natural capital into account [3]. In practical terms, the balance compares economic performance with resource intensity, emissions, and other environmental losses.

$$B_1 = \alpha_1 G + \beta_1 E, \quad \textbf{(5)}$$

where *G* is the normalized index of economic dynamics; *E* is the normalized environmental security index in formula (5).

If pollution indicator *P* is used in the model as a destimulant, the alternative adjusted form is given in formula (6):

$$B_1^* = G - \gamma P. \quad \textbf{(6)}$$

IEA data indicate substantial investment in clean energy [4], while China's experience shows that clean-energy sectors accounted for more than 10% of GDP in 2024 and about one quarter of its growth [10]. This confirms that green transformation can be not only a source of costs but also a factor of structural economic growth.

Balance Between Economic Efficiency and Social Justice

The economic performance of regional development cannot be assessed exclusively through profit or productivity. A. Sen's approach links development to the expansion of human capabilities [12], while J. Rawls justifies inequality only when it improves the position of the least advantaged [13]. Therefore, the partial balance should be defined as:

$$B_2 = \alpha_2 Econ + \beta_2 Soc, \quad \textbf{(7)}$$

where *Econ* is the normalized economic-efficiency index; *Soc* is the normalized social-justice index.

When the Gini coefficient is used as a destimulant, the adjusted form (8) may be applied:

$$B_2^* = Eff - \delta \cdot \text{Gini}. \quad \textbf{(8)}$$

Table 1

System of Basic Sustainable Territorial Development Balances and Examples of Indicators

Balance	Benefit component X	Resilience component Y	Examples of indicators
B_1 – Economic growth – environmental security	Economic dynamics	Environmental security	– GDP growth rate; productivity / emissions, resource intensity, environmental condition; – GRP volume index / emissions
B_2 – Economic efficiency – social justice	Productivity, employment	Social inclusion	– Productivity, employment / Gini, poverty risk, access to services; – GRP per capita / unemployment
B_3 – Current consumption – future generations	Current well-being	Capital preservation	– Consumption / natural capital, savings, resource stock; – disposable income / capital investment
B_4 – Economic openness – economic security	Integration	Resilience and autonomy	– Trade, FDI / import concentration, energy dependence, supply-chain resilience; – foreign trade / export-to-import coverage ratio

Source: compiled by the author.

Practical manifestations of imbalance arise when a socially oriented decision increases the income of a target group but simultaneously creates a risk of reduced employment or higher employer costs. Assessment should therefore include both sides of the effect.

Balance Between Current Consumption and the Interests of Future Generations

Intergenerational equity requires that current well-being not be achieved at the cost of an irreversible reduction in the opportunities available to future generations. R. Solow emphasized the need to transfer an adequate stock of capital to subsequent generations [22], while Hartwick's rule calls for investing rents from non-renewable resources in other forms of capital [23]. In generalized form, intertemporal utility can be represented as:

$$U = \Sigma_{t=0}^{T} C_t / (1 + \rho)^t. \quad \textbf{(9)}$$

For natural capital, the basic balance relationship takes the form (10):

$$N_{t+1} = N_t - R_t + I_t, \quad \textbf{(10)}$$

where N_t is the stock of natural capital; R_t is resource extraction; I_t is restoration, compensatory, or replacement investment.

In simplified form, the condition of weak sustainability requires preventing a systematic decline in the combined stock of reproducible and natural capital.

Balance Between Economic Openness and Economic Security

Openness provides access to markets, capital, technologies, and innovation, but excessive import concentration or dependence on critical external suppliers increases vulnerability to adverse shocks. This contradiction is consistent with D. Rodrik's argument concerning the limits of excessive global integration [24]. Based on the above, the partial index characterizing the balance between economic openness and economic security is presented in formula (11):

$$B_4 = \alpha_4 Open + \beta_4 Sec, \quad \textbf{(11)}$$

where *Open* is the normalized economic-openness index; *Sec* is the normalized economic-security index.

When external-dependence indicator *D* is used directly, the adjusted form (12) is appropriate:

$$B_4^* = O - \lambda D. \quad \textbf{(12)}$$

For territorial policy, this means that increases in exports, imports, or foreign direct investment (FDI) should be assessed together with supplier diversification, energy resilience, and the reliability of critical infrastructure.

Integral Model and Its Difference from SDG/ESG Approaches

The scientific novelty of the proposed approach lies not in creating another list of indicators, but in

changing the logic of their aggregation and distinguishing two analytical characteristics: the level of simultaneous achievement of paired objectives (B_j) and the degree of their internal coherence (C_j). SDG indicators characterize achievement of individual goals, while ESG metrics characterize the environmental, social, and governance features of organizations or investments. The proposed model groups indicators into pairs of potentially conflicting objectives and makes it possible to assess both performance and imbalance between them separately.

An additional way to limit the compensation effect is geometric aggregation of components according to formula (13), which responds more strongly to a critically low value of one component:

$$B_j^G = X_j \wedge \alpha_j \cdot Y_j \wedge \beta_j. \quad \textbf{(13)}$$

Geometric aggregation reduces the aggregate estimate more strongly when one component approaches zero, but it does not replace the coherence coefficient C_j: the geometric index characterizes the non-compensatory level of joint objective achievement, whereas C_j directly measures the gap between them. Thus, linear B_j, its geometric variant, and C_j perform different but complementary analytical functions.

RESEARCH RESULTS AND EMPIRICAL TESTING OF THE SUSTAINABLE DEVELOPMENT BALANCE SYSTEM

Information Base and Parameters of Empirical Testing

The proposed methodology was empirically tested using official 2021 statistics of the State Statistics Service of Ukraine for 24 regions of Ukraine and the city of Kyiv [29; 30]. The Autonomous Republic of Crimea and the city of Sevastopol were excluded from the sample because fully comparable statistical observations were unavailable. Donetsk and Luhansk regions, by contrast, were included using official regional data published without the temporarily occupied territories. For methodological comparability, the same territorial-coverage principle should be applied to each of the eight primary indicators.

Eight main indicators were used to assess the four balances:

1) GRP volume index – a measure of economic dynamics;

2) emissions of pollutants from stationary sources per 1 km^2 – a measure of environmental pressure;

3) GRP per capita – a measure of economic performance;

4) unemployment rate of the population aged 15–70 – a measure of social inclusion;

5) disposable household income per capita – a measure of current well-being;

6) capital investment per capita – a proxy for the formation of future productive and infrastructure capital;

7) foreign-trade intensity – the ratio of the sum of exports and imports to GRP;

8) export-to-import coverage ratio – a proxy for external economic resilience.

Data on GRP and its volume index were obtained from official statistics of the State Statistics Service of Ukraine. In 2021, Ukraine's GRP amounted to UAH 5,450.849 million and its volume index was 103.4% of the previous year. GRP per capita amounted to UAH 131.734 [30].

Disposable household income also showed substantial interregional differentiation, ranging from UAH 31,390 per capita in Luhansk region to UAH 211.620 in the city of Kyiv [29].

According to the ILO methodology, the unemployment rate in 2021 ranged from 6.7% in Kharkiv region to 16.0% in Luhansk region; in the city of Kyiv it was 7.1% [29].

The environmental component was characterized using emissions from stationary pollution sources per unit of area. In 2021, this indicator ranged from 0.2 t/km^2 in Chernivtsi and Zakarpattia regions to 46.4 t/km^2 in the city of Kyiv, indicating substantial territorial differentiation in environmental pressure [29].

Capital investment was used to assess the investment component. In 2021, its total volume in Ukraine was UAH 528.8 billion, with the largest absolute amounts recorded in the city of Kyiv, Dnipropetrovsk region, and Kyiv region [29].

In 2021, merchandise exports amounted to USD 68,072.3 million and imports to USD 72,843.1 million. Regional differentiation was very substantial: the city of Kyiv accounted for 22.5% of exports and 42.6% of imports, while Dnipropetrovsk region accounted for 17.9% and 8.1%, respectively [29].

Formation of Normalized Indicators for Empirical Testing

The general procedure for min–max normalization of stimulant and destimulant indicators, as well as the principles for determining weights, is presented in Section 4 in formulas (1) and (2). This subsection specifies only the set of indicators used for testing across Ukrainian regions in 2021 and the direction of their impact.

Five indicators were classified as stimulants: the GRP volume index; GRP per capita; disposable household income per capita; capital investment per capita; and foreign-trade intensity. The export-to-import coverage ratio was also normalized in the direct direction as an indicator of external economic resilience. Two in-

dicators were classified as destimulants: the unemployment rate of the population aged 15–70 and emissions of pollutants from stationary sources per 1 km^2.

The x_{min} and x_{max} normalization boundaries were determined using the actual minimum and maximum values of each indicator in the common regional sample. The information-base section directly provides the ranges for three indicators: disposable household income – UAH 31.390–211.620 per capita; unemployment — 6.7–16.0%; and stationary-source emissions – 0.2–46.4 t/km^2.

Formation of Partial Balances in the Calculation Model

Partial indices B_1–B_4 were calculated using general formula (3) with baseline equal component weights. Under the refined interpretation, these indices characterize the level of simultaneous achievement of the respective pairs of objectives; the degree of their coherence is additionally characterized by coefficient C_j according to formula (14):

$$C_j = 1 - |X_j - Y_j|. \quad \textbf{(14)}$$

In the empirical test, B_1 combines the normalized GRP volume index and the normalized environmental-security indicator; B_2 combines normalized GRP per capita and the normalized social-inclusion indicator; B_3 combines normalized disposable household income per capita and normalized capital investment per capita; and B_4 combines normalized foreign-trade intensity and the normalized export-to-import coverage ratio. The integral SD index is determined using the aggregation procedure presented in Section 4.

Results of Calculating the Balance System

The calculated partial balances and integral index are presented in *Tbl. 2*.

The results in Tbl. 2 demonstrate not only substantial differentiation in the integral level of sustainable development across Ukrainian regions but also fundamentally different structures underlying that result. The integral index ranges from 0.198 in Luhansk region to 0.682 in the city of Kyiv; however, the same or a similar integral score may arise from different combinations of economic, social, environmental, and external-economic components. This confirms the need to analyze not only the final SD index but also the configuration of the four partial balances B_1–B_4.

The city of Kyiv has the highest integral result (*SD* = 0.682), but its structure is distinctly asymmetric. It is driven primarily by the highest values in the sample for the balance between current well-being and future capital formation (B_3 = 1.000) and the balance between economic efficiency and social inclusion (B_2 = 0.978). The economic basis of this result is the concentration of economic activity, high incomes, and capital investment in the capital city. At the same time, the substantially lower B_1 = 0.355 indicates a contradiction between the high concentration of economic activity and environmental security. This is consistent with the primary data: Kyiv records the highest disposable household income in the sample, substantial capital investment, and at the same time the highest density of stationary-source emissions — 46.4 t/km^2. Thus, the capital's development model delivers strong economic and social outcomes but is accompanied by considerable environmental pressure.

Mykolaiv region ranks second (*SD* = 0.582), but the nature of its result is fundamentally different. The exceptionally high B_1 = 0.997 reflects a favorable combination of economic dynamics and relatively low environmental pressure, while B_4 = 0.777 reflects the substantial role of external economic activity. At the same time, B_2 = 0.361 and especially B_3 = 0.193 are considerably lower. This means that the region's economic dynamics and external openness are not proportionally transformed into current household well-being and future capital formation. Thus, Mykolaiv region's high *SD* is largely generated by two strong components and does not imply uniformly high development across all dimensions.

Among the leading regions, Dnipropetrovsk region (*SD* = 0.540) demonstrates the most even structure of sustainable-development indicators. Its B_1 = 0.632, B_2 = 0.581, B_3 = 0.385, and B_4 = 0.564 do not display the sharp dominance of one or two components seen in Kyiv or Mykolaiv region. The economic basis of this result is its powerful industrial complex, substantial investment activity, and strong participation in foreign trade: in 2021 the region accounted for 17.9% of Ukrainian exports and was among the leaders in absolute capital investment. At the same time, industrial specialization creates environmental constraints, so economic potential does not produce the maximum B_1. The resulting configuration characterizes Dnipropetrovsk region as a territory with relatively diversified sources of its integral result, albeit with substantial environmental challenges.

Zaporizhzhia region (*SD* = 0.514) is also characterized by an industrial-export model: high B_1 = 0.813 and B_4 = 0.583 are combined with substantially lower B_2 = 0.403 and B_3 = 0.257. This structure indicates that the region's economic dynamics and external orientation outpace the social and investment component of development. Therefore, high productive and export potential alone does not ensure equally high levels of current well-being, social inclusion, and capital accumulation.

Kyiv region (*SD* = 0.507) has a different configuration: relatively high B_1 = 0.763 and B_2 = 0.643 are

Table 2

Assessment Results for the Sustainable Development Balance System of Ukrainian Regions, 2021

Region	B_1	B_2	B_3	B_4	SD
Vinnytsia	0.874	0.379	0.209	0.273	0.434
Volyn	0.499	0.258	0.153	0.285	0.299
Dnipropetrovsk	0.632	0.581	0.385	0.564	0.540
Donetsk	0.531	0.087	0.097	0.823	0.385
Zhytomyr	0.865	0.346	0.182	0.175	0.392
Zakarpattia	0.790	0.308	0.099	0.582	0.445
Zaporizhzhia	0.813	0.403	0.257	0.583	0.514
Ivano-Frankivsk	0.643	0.471	0.145	0.253	0.378
Kyiv	0.763	0.643	0.345	0.275	0.507
Kirovohrad	0.907	0.254	0.166	0.544	0.468
Luhansk	0.750	0.000	0.000	0.040	0.198
Lviv	0.903	0.562	0.222	0.274	0.490
Mykolaiv	0.997	0.361	0.193	0.777	0.582
Odesa	0.913	0.579	0.228	0.142	0.466
Poltava	0.720	0.404	0.311	0.346	0.445
Rivne	0.799	0.409	0.134	0.211	0.389
Sumy	0.697	0.411	0.194	0.265	0.392
Ternopil	0,934	0.288	0.154	0.226	0.400
Kharkiv	0.743	0.620	0.212	0.122	0.424
Kherson	0.838	0.303	0.149	0.172	0.365
Khmelnytskyi	0.899	0,395	0.187	0.228	0.427
Cherkasy	0.857	0.425	0.185	0.158	0.406
Chernivtsi	0.827	0.405	0.104	0.093	0.357
Chernihiv	0.800	0.307	0.181	0.406	0.424
City of Kyiv	0.355	0.978	1.000	0.394	0.682

Note: SD is the integral index of the balance system; all indicators are normalized to the [0; 1] interval.
Source: compiled by the author.

combined with B_3 = 0.345 and B_4 = 0.275. This indicates fairly strong economic and social components, but a weaker position in the relationship between current well-being and future capital accumulation, as well as in the external-economic balance. Thus, proximity to the country's largest economic center and high economic activity do not eliminate structural constraints on the region's long-term and external-economic development.

A separate group consists of regions with high B_1 but comparatively modest overall *SD*. These include Ternopil (B_1 = 0.934; *SD* = 0.400), Zhytomyr (0.865; 0.392), Khmelnytskyi (0.899; 0.427), Vinnytsia (0.874; 0.434), and Kherson (0.838; 0.365) regions. The high value of the first balance in these regions is not accompanied by similarly high socioeconomic and external-economic results. This is an important finding: a relatively favorable relationship between economic dynamics and environmental pressure is not a sufficient condition for a high integral level of sustainable development.

For most regions, the most problematic component is the third balance – between current well-being and the formation of conditions for the development of future generations. Except for the city of Kyiv, B_3 is low in most regions; it equals zero in Luhansk region, 0.097 in Donetsk, 0.099 in Zakarpattia, 0.104 in Chernivtsi, and 0.134 in Rivne region. Because this balance is represented in the empirical model by disposable household income and capital investment per capita, the results point to a systemic problem of insufficient linkage between current income levels and the accumulation of productive and infrastructure

capital. Thus, insufficient investment capacity across a substantial share of territories is one of the key obstacles to a more balanced regional model.

Luhansk region is an extreme case of a structurally weak balance model: SD = 0.198 with B_2 = 0.000, B_3 = 0.000, and B_4 = 0.040. The socioeconomic causes are already reflected in the primary data: the region has the lowest disposable household income in the sample – UAH 31.390 per capita – and the highest unemployment rate – 16.0%. This combination directly weakens the social and intertemporal components of the model. The result should also be viewed in the context of the specific conditions under which the regional economy operated in 2021 and the incomplete territorial coverage of official statistics due to the temporary occupation of part of the territory. The low score therefore reflects not only ordinary interregional structural differences but also the region's special institutional and economic conditions.

A synthesis of the results in *Tbl. 2* makes it possible to distinguish at least three types of regional models. The first is represented by the city of Kyiv – a high integral result driven by the concentration of income, economic activity, and investment amid substantial environmental and external-economic disparities. The second type, characteristic of Mykolaiv, Zaporizhzhia, and partly other industrial-export regions, is based on strong economic and/or external-economic components with weaker social and investment support. The third type is represented by Dnipropetrovsk region, where the integral result is formed more evenly across several components. Regions with a low overall level of objective achievement form a separate group, with Luhansk region being the clearest example.

The main economic conclusion is therefore that a high SD value is not, by itself, sufficient evidence of balanced sustainable development. It may result from a concentration of economic activity, income, investment, or foreign trade, while weak environmental, social, or long-term components are partially offset by stronger ones. The results in Tbl. 2 should therefore be treated as an assessment of the level of achievement of paired objectives, while the final conclusion regarding their balance should be made jointly with the C_1–C_4 coherence coefficients and the geometric index presented in the following tables.

Calculation of Coherence Coefficients C_1–C_4 and Adjusted Indices B_j^*

To assess "balance" itself rather than merely the level of joint objective achievement, further empirical verification should include the calculation of C_1–C_4 coefficients (or adjusted B_j^*) alongside B_1–B_4. This makes it possible to directly distinguish a high level of two components from their mutual coherence.

For each pair, $C_j = 1 - |X_j - Y_j|$ and $B_j^* = B_j \cdot C_j$ were calculated. A high C_j indicates proximity between the two components but does not necessarily imply a high level of development: for example, in Luhansk region $C_2 = C_3 = 1.000$ occurs when both components are close to zero. Therefore, C_j must be interpreted only together with B_j or B_j^*. The C_1–C_4 results together with B_1–B_4, SD, and SDg are presented in *Tbl. 3*.

Adjusted B_j^* values are calculated in the full matrix in *Tbl. 6* (*a* – *d*). Their use substantially reduces the assessment of situations in which the average B_j level is generated by one dominant component.

Tbl. 3 confirms that a high coherence coefficient is not, by itself, evidence of a high level of sustainable development. The clearest example is Luhansk region, where C_2 and C_3 equal 1.000 while B_2 and B_3 are both zero. Economic interpretation therefore requires joint analysis of the level of objective achievement and their coherence.

Considering all four C coefficients, Zaporizhzhia and Mykolaiv regions demonstrate the most coherent profiles: in both cases all C_1–C_4 exceed 0.7. However, their quality differs substantially in terms of partial outcomes: in Mykolaiv region high internal coherence of individual pairs is combined with a low B_3, whereas Zaporizhzhia region has a more moderate gap among partial results. Dnipropetrovsk region stands out for combining relatively even B_1–B_4 with high coherence in three of the four pairs, making its structure one of the most resilient in the sample.

The most pronounced local imbalances in terms of C are observed in Volyn region for the first balance, in Zakarpattia and Kirovohrad regions for the fourth, in Kharkiv and Odesa regions for the second, and in the city of Kyiv for the first and fourth balances. This shows that structural problems have different economic origins and cannot be reduced to a single ranking. For regional policy, this means that targeted intervention is required precisely in the pair of objectives where the combination of level and coherence is weakest.

Analysis of the Structure of Imbalances

Comparison of the partial indices makes it possible to identify different types of regional development models.

The first type comprises economically and investment-strong regions with environmental constraints. These include the city of Kyiv, Dnipropetrovsk region, and Zaporizhzhia region.

The second type comprises regions with a strong environmental-economic base but insufficient social

Table 3

Coherence Coefficients C_1–C_4 and Integral Indices for Ukrainian Regions, 2021

Region	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	SD	SDg
Vinnytsia	0.874	0.379	0.209	0.273	0.869	0.683	0.857	0.680	0.434	0.371
Volyn	0.499	0.258	0.153	0.284	0.002	0.806	0.928	0.431	0.299	0.274
Dnipropetrovsk	0.632	0.581	0.385	0.563	0.983	0.635	0,924	0.862	0.540	0.531
Donetsk	0.531	0.087	0.097	0.823	0.729	0.955	0.986	0.647	0.385	0.246
Zhytomyr	0.865	0.346	0.182	0.174	0.739	0.660	0.868	0.944	0.392	0.312
Zakarpattia	0.790	0.308	0.099	0.581	0.580	0.562	0.893	0.163	0.445	0.344
Zaporizhzhia	0.813	0.403	0.257	0.584	0.855	0.752	0.825	0.974	0.514	0.471
Ivano-Frankivsk	0.643	0.471	0.145	0.252	0.813	0.372	0.878	0.932	0.378	0.324
Kyiv	0.763	0.643	0.345	0.275	0.610	0.394	0.970	0.449	0.507	0.465
Kirovohrad	0.907	0.254	0.166	0.543	0.828	0,906	0.869	0.227	0.467	0.380
Luhansk	0.750	0.000	0.000	0.040	0.549	1.000	1.000	0.970	0.198	0.000
Lviv	0.903	0.562	0.222	0.273	0.947	0.339	0.847	0.551	0.490	0.419
Mykolaiv	0.997	0.361	0.193	0.777	0.994	0.711	0.826	0.943	0.582	0.482
Odesa	0.913	0.579	0.228	0.140	0.865	0.287	0.772	0.885	0.465	0.361
Poltava	0.720	0.404	0.311	0.346	0.511	0.966	0.947	0.931	0.445	0.421
Rivne	0.799	0.409	0.134	0.211	0.612	0.442	0.865	0.956	0.388	0.310
Sumy	0.697	0.411	0.194	0.265	0.421	0.553	0.812	0.948	0.392	0.348
Ternopil	0.934	0.288	0.154	0.226	0.885	0.694	0.934	0.949	0.400	0.311
Kharkiv	0.743	0.620	0.212	0.122	0.576	0.240	0.786	0.934	0.424	0.330
Kherson	0.838	0.303	0.149	0.172	0.694	0.703	0.829	0.675	0.365	0.284
Khmelnytskyi	0.899	0.395	0.187	0.228	0.832	0.564	0.883	0.842	0.427	0.351
Cherkasy	0.857	0.425	0.185	0.158	0.805	0.581	0.867	0.918	0.406	0.321
Chernivtsi	0.827	0.405	0.104	0.094	0.655	0.369	0.873	0.813	0.357	0.239
Chernihiv	0.800	0.307	0.181	0.406	0.622	0.840	0.892	0.584	0.423	0.366
City of Kyiv	0.355	0.978	1.000	0.392	0.290	0.958	1.000	0.234	0.681	0.608

Source: compiled by the author.

and investment components. These include, in particular, Kirovohrad, Ternopil, Zhytomyr, and Khmelnytskyi regions.

The third type comprises regions with high external economic activity but internal imbalance. Examples include Donetsk and Mykolaiv regions.

The fourth type comprises comprehensively vulnerable territories characterized by low values of several balances simultaneously, particularly Luhansk region.

Thus, the integral index provides a generalized assessment, while the system of partial balances makes it possible to identify the causes of imbalances, which is a key advantage of the proposed approach. This is the fundamental difference between the proposed approach and simple ranking-based assessment.

Verification of Results Using Geometric Aggregation

To assess the impact of the compensation effect, the geometric index was calculated using formula (15):

$$SDg = (B_1B_2B_3B_4)^{\wedge}(1/4). \quad \textbf{(15)}$$

Unlike the arithmetic approach, geometric aggregation substantially reduces the integral estimate when individual components have critically low values.

The results generally confirm the baseline conclusions but refine the ranking of regions. In particular, the city of Kyiv retains the leading position ($SDg \approx 0.608$), while Dnipropetrovsk region has $SDg \approx 0.531$. At the same time, regions with pronounced imbalances receive substantially lower index values.

Thus, combining arithmetic and geometric aggregation makes it possible to identify the degree of

compensation among the components of sustainable development.

For a more complete interpretation, arithmetic *SD* and geometric *SDg* should be treated as two equally important results. Their difference characterizes the compensation gap: the larger it is, the more strongly a relatively high integral territorial result is supported by stronger partial balances compensating for weaker ones. The compensation gap is defined by formula (16):

$$\Delta comp = SD - SDg. \quad \textbf{(16)}$$

The calculated compensation-gap values are presented in *Tbl. 4*.

Table 4

Compensation Gap Between the Arithmetic and Geometric Integral Indices

Region	SD	SDg	Δcomp = SD – SDg
Vinnytsia	0.434	0.371	0.063
Volyn	0.299	0.274	0.025
Dnipropetrovsk	0.540	0.531	0.009
Donetsk	0.385	0.246	0.139
Zhytomyr	0.392	0.312	0.080
Zakarpattia	0.445	0.344	0.101
Zaporizhzhia	0.514	0.471	0.043
Ivano-Frankivsk	0.378	0.324	0.054
Kyiv	0.507	0.465	0.042
Kirovohrad	0.467	0.380	0.087
Luhansk	0.198	0.000	0.198
Lviv	0.490	0.419	0.071
Mykolaiv	0.582	0.482	0.100
Odesa	0.465	0.361	0.104
Poltava	0.445	0,421	0.024
Rivne	0.388	0.310	0.078
Sumy	0.392	0.348	0.044
Ternopil	0.400	0.311	0.089
Kharkiv	0.424	0.330	0.094
Kherson	0.365	0.284	0.081
Khmelnytskyi	0.427	0.351	0.076
Cherkasy	0.406	0.321	0.085
Chernivtsi	0.357	0.239	0.118
Chernihiv	0.423	0.366	0.057
City of Kyiv	0.681	0.608	0.073

Source: compiled by the author.

The results in Tbl. 4 make it possible to assess the extent to which the arithmetic integral index overstates the perception of development resilience due to mutual compensation between strong and weak components. The smallest compensation gap is found in Dnipropetrovsk region (0.009), followed by Poltava (0.024), Volyn (0.025), Kyiv (0.042), and Zaporizhzhia (0.043) regions. For these regions, switching to geometric aggregation changes the final assessment relatively little, indicating lower dependence of the integral result on stronger components compensating for critically weak partial balances.

The largest compensation gap is recorded in Luhansk (0.198), Donetsk (0.139), Chernivtsi (0.118), Odesa (0.104), Zakarpattia (0.101), and Mykolaiv (0.100) regions. In these regions, arithmetic SD is substantially supported by individual strong components, while the geometric index reacts more strongly to weak links in the system. The comparison of Mykolaiv and Dnipropetrovsk regions is particularly illustrative: the former has a higher arithmetic *SD* but a much larger compensation gap, whereas *SD* and *SDg* almost coincide in Dnipropetrovsk region. From the standpoint of structural resilience, a high integral result should therefore be regarded as higher quality when it is combined with a small compensation gap. For the city of Kyiv, $\Delta comp = 0.073$ indicates a moderate compensation effect: the capital retains its leading position, but it should be interpreted with regard to the unevenness of individual components.

Sensitivity Analysis with Respect to Weighting Coefficients

To test the robustness of the results, sensitivity analysis was conducted by varying component weights within 0.3–0.7 while maintaining their sum at 1.

The results show that the city of Kyiv consistently retains first place under most scenarios. Dnipropetrovsk and Zaporizhzhia regions also demonstrate high robustness.

The ranges of variation in the integral index are:
– city of Kyiv: 0.606–0.758;
– Mykolaiv region: 0.556–0.608;
– Dnipropetrovsk region: 0.511–0.570;
– Zaporizhzhia region: 0.485–0.544.

The results indicate that the main conclusions regarding the group of leaders are not solely a consequence of choosing equal weights. At the same time, changing the weights may substantially alter the positions of individual regions, confirming the need for sensitivity analysis in practical applications of the model.

Robustness Check Using Alternative Normalization and Weights

An additional robustness check was conducted in two directions. First, instead of conventional min–max normalization, robust min-max normalization with values winsorized at the 5th and 95th percentiles was applied. Spearman's rank correlation between the

baseline *SD* and the robust variant is ρ = 0.955, indicating high but not absolute ranking stability. Under the robust scenario, the leading positions are occupied by Dnipropetrovsk region, the city of Kyiv, Kyiv region, Mykolaiv region, and Zaporizhzhia region; thus, extreme values partly affect the ordering of the leaders. Second, asymmetric weights of 0.4/0.6 and 0.6/0.4 were tested for each pair. The corresponding rank correlations with the baseline *SD* are ρ = 0.985 and ρ = 0.991. The group of five leaders is preserved when the weights change, although the internal ordering of individual regions may vary (see *Tbl. 5*). This confirms the overall robustness of the main conclusions and at the same time substantiates the need to publish scenario results together with baseline estimates.

Table 5

Robustness of Regional Rankings to Alternative Normalization and Weights

Scenario	Spearman ρ with baseline SD	Top 5 regions
Robust min-max (5–95%)	0,955	Dnipropetrovsk; City of Kyiv; Kyiv; Mykolaiv; Zaporizhzhia
X/Y weights = 0.4/0.6	0,985	City of Kyiv; Mykolaiv; Dnipropetrovsk; Zaporizhzhia; Kyiv
X/Y weights = 0.6/0.4	0,991	City of Kyiv; Mykolaiv; Dnipropetrovsk; Zaporizhzhia; Kyiv

Source: compiled by the author.

The additional empirical check refined the study's conclusions. The extreme B_1 = 0.997 for Mykolaiv region is arithmetically reproduced from the primary data and is due to the combination of the maximum GRP volume index (108.7%) and low stationary-emission density (about 0.48 t/km^2). Calculation of C_1–C_4 showed that the level of objective achievement and their coherence are indeed different characteristics; therefore, substantive interpretation should use B_j and C_j simultaneously or the adjusted B_j^*. Robust normalization and asymmetric weights showed high rank stability of the results (Spearman's ρ = 0.955–0.991), although the order of individual leaders depends on the normalization method. Further extension of the model should include direct indicators of natural-capital stocks and reproduction, resource productivity, energy dependence, concentration of critical imports, supplier diversification, and critical-infrastructure resilience. The full primary and normalized matrix is provided in *Tbl. 6* (*a* – *d*).

Interpretation of Results for Regional Policy

The calculations make it possible to formulate a fundamentally important conclusion: a high level of an individual indicator is not a sufficient condition for sustainable territorial development.

For example, the city of Kyiv has the maximum B_3 value, but its B_1 is substantially lower because of high environmental pressure. Therefore, policy for the capital's further economic development should focus not so much on increasing economic output as on reducing the environmental cost of that output.

For Mykolaiv region, the key task is to strengthen the intergenerational component by increasing investment capacity and forming long-term capital.

For Dnipropetrovsk and Zaporizhzhia regions, it is advisable to maintain high economic performance while simultaneously reducing environmental pressure and increasing social inclusion.

For regions with high B_1 but low B_2 and B_3 – particularly Ternopil, Zhytomyr, Khmelnytskyi, and Kirovohrad – the priority should be to increase productivity, employment, household income, and investment activity.

Territories with critically low values of several balances require comprehensive structural-transformation programs, because improving only one indicator will not restore overall resilience.

Thus, the proposed model can be used not only to rank regions but also to identify the specific type of imbalance and the corresponding direction of regional policy.

Summary of Empirical Testing Results

The empirical test confirms the operability of the proposed balance system. Unlike traditional integral assessment, in which different indicators may offset one another without meaningful grouping, the proposed model makes it possible to proceed sequentially through three levels of analysis:

1. Assess individual statistical characteristics.
2. Determine partial balances between competing objectives.
3. Form an integral assessment of the sustainability of territorial development.

At the same time, the integral assessment should not be treated as a self-sufficient criterion. Arithmetic *SD* and geometric *SDg* should be interpreted as two equally important results: the former shows the average level of partial balances under full compensation, while the latter is a non-compensatory result sensitive to weak components. Their difference, Δ*comp* = *SD* – *SDg*, additionally indicates the strength of the compensation effect (see Tbl. 4).

The 2021 results are generally consistent with the main research hypothesis: regions may have high

Table 6

Primary and Normalized Calculation Matrix for Ukrainian Regions, 2021

Table 6a. Primary indicators

Region	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Vinnytsia	105.6	3.002	114218	11.0	81970	9327	0.01157	1.87
Volyn	92.5	0.292	90331	12.7	65481	8166	0.02860	0.46
Dnipropetrovsk	102.6	16.807	186697	8.9	107671	21183	0.03097	2.07
Donetsk	103.3	28.136	69446	15.4	47604	7440	0.03152	3.72
Zhytomyr	104.4	0.411	95948	11.2	76107	8111	0.01282	1.12
Zakarpattia	101.9	0.211	60632	11.1	58844	4136	0.04472	0.99
Zaporizhzhia	104.5	5.501	138521	11.1	93475	11148	0.02965	2.32
Ivano-Frankivsk	101.4	12.368	88227	8.7	68561	6292	0.01806	1.17
Kyiv	101.7	2.136	162696	7.2	96293	20228	0.02794	0.46
Kirovohrad	105.8	0.523	109183	13.2	73146	7230	0.01320	3.49
Luhansk	101.0	1.341	24684	16.0	31390	1550	0.00829	0.64
Lviv	106.7	3.459	119049	7.7	85195	9786	0.02596	0.62
Mykolaiv	108.7	0.477	112864	11.3	81870	7547	0.03746	2.90
Odesa	106.2	1.109	115129	7.3	93001	8013	0.01476	0.73
Poltava	100.2	1.831	195825	12.4	92260	17645	0.01901	1.70
Rivne	102.3	0.521	77599	9.6	67727	5309	0.01441	1.22
Sumy	99.1	0.819	100760	10.1	83307	7208	0.01823	1.24
Ternopil	106.7	0.595	79412	11.9	65084	8404	0.01484	1.28
Kharkiv	101.1	2.273	122227	6.7	88863	7501	0.01314	0.75
Kherson	103.6	0.624	87378	11.8	73624	5155	0.00771	1.55
Khmelnytskyi	105.7	0.977	96964	10.3	75606	8835	0.01290	1.46
Cherkasy	104.8	2.291	112145	10.1	76673	8273	0.01478	0.84
Chernivtsi	103.1	0.215	61088	9.3	61612	3833	0.00736	1.07
Chernihiv	102.4	0.713	117225	12.4	73742	8741	0.01475	2.46
City of Kyiv	104.0	46.394	431616	7.1	211620	58168	0.03633	0.49

Table 6b. Normalized indicators

Region	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
1	2	3	4	5	6	7	8	9
Vinnytsia	0.809	0.939	0.220	0.538	0.281	0.137	0.113	0.433
Volyn	0.000	0.998	0.161	0.355	0.189	0.117	0.569	0.000
Dnipropetrovsk	0.623	0.641	0.399	0.763	0.423	0.347	0.632	0.494
Donetsk	0.667	0.395	0.109	0.065	0.090	0.104	0.647	1.000
Zhytomyr	0.735	0.995	0.176	0.516	0.248	0.116	0.146	0.202
Zakarpattia	0.580	1.000	0.089	0.527	0.152	0.046	1.000	0.163
Zaporizhzhia	0.741	0.885	0.279	0.527	0.344	0.170	0.597	0.571
Ivano-Frankivsk	0.549	0.737	0.157	0.785	0.206	0.084	0.286	0.218
Kyiv	0.568	0.958	0.340	0.946	0.360	0.330	0.551	0.000
Kirovohrad	0.821	0.993	0.207	0.301	0.232	0.100	0.156	0.929
Luhansk	0.525	0.975	0.000	0.000	0,000	0,000	0.025	0.055
Lviv	0.877	0.929	0.232	0.892	0.299	0.145	0.498	0.049

End of the Tbl. 6b

1	2	3	4	5	6	7	8	9
Mykolaiv	1.000	0.994	0.217	0.505	0.280	0.106	0.806	0.748
Odesa	0.846	0.980	0.223	0.935	0.342	0.114	0.198	0.083
Poltava	0.475	0.965	0.421	0.387	0.338	0.284	0.312	0.380
Rivne	0.605	0.993	0.130	0.688	0.202	0.066	0.189	0.233
Sumy	0.407	0.987	0.188	0.634	0.288	0.100	0.291	0.239
Ternopil	0.877	0.991	0.135	0.441	0.187	0.121	0.200	0.252
Kharkiv	0.531	0.955	0.240	1.000	0.319	0.105	0.155	0.089
Kherson	0.685	0.991	0.154	0.452	0.234	0.064	0.009	0.334
Khmelnytskyi	0.815	0.983	0,177	0.613	0.245	0.129	0.148	0.307
Cherkasy	0.759	0.955	0.216	0.634	0.251	0.119	0.199	0.117
Chernivtsi	0.654	1.000	0.090	0.720	0.168	0.040	0.000	0.187
Chernihiv	0.611	0.989	0.227	0.387	0.235	0.127	0.198	0.613
City of Kyiv	0.710	0.000	0.999	0.957	1.000	1.000	0.775	0.009

Table 6c. Partial balances and coherence coefficients

Region	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4
Vinnytsia	0.874	0.379	0.209	0.273	0.869	0.683	0.857	0.680
Volyn	0.499	0.258	0.153	0.284	0.002	0.806	0.928	0.431
Dnipropetrovsk	0.632	0.581	0.385	0.563	0.983	0.635	0.924	0.862
Donetsk	0.531	0.087	0.097	0.823	0.729	0.955	0.986	0.647
Zhytomyr	0.865	0.346	0.182	0.174	0.739	0.660	0.868	0.944
Zakarpattia	0.790	0.308	0.099	0.581	0.580	0.562	0.893	0.163
Zaporizhzhia	0.813	0.403	0.257	0.584	0.855	0.752	0.825	0.974
Ivano-Frankivsk	0.643	0.471	0.145	0.252	0.813	0.372	0.878	0.932
Kyiv	0.763	0.643	0.345	0.275	0.610	0.394	0.970	0.449
Kirovohrad	0.907	0.254	0.166	0.543	0.828	0.906	0.869	0.227
Luhansk	0.750	0.000	0.000	0.040	0.549	1.000	1.000	0.970
Lviv	0.903	0.562	0.222	0.273	0.947	0.339	0.847	0.551
Mykolaiv	0.997	0.361	0.193	0.777	0.994	0.711	0.826	0.943
Odesa	0.913	0.579	0.228	0.140	0.865	0.287	0.772	0.885
Poltava	0.720	0.404	0.311	0.346	0.511	0.966	0.947	0.931
Rivne	0.799	0.409	0.134	0.211	0.612	0.442	0.865	0.956
Sumy	0.697	0.411	0.194	0.265	0.421	0.553	0.812	0.948
Ternopil	0.934	0.288	0.154	0.226	0.885	0.694	0.934	0.949
Kharkiv	0.743	0.620	0.212	0.122	0.576	0.240	0.786	0.934
Kherson	0.838	0.303	0.149	0.172	0.694	0.703	0.829	0.675
Khmelnytskyi	0.899	0.395	0.187	0.228	0.832	0.564	0.883	0.842
Cherkasy	0.857	0.425	0.185	0.158	0.805	0.581	0.867	0.918
Chernivtsi	0.827	0.405	0.104	0.094	0.655	0.369	0.873	0.813
Chernihiv	0.800	0.307	0.181	0.406	0.622	0.840	0.892	0.584
City of Kyiv	0.355	0.978	1.000	0.392	0.290	0.958	1.000	0.234

Table 6d. Adjusted and integral indices

Region	B_1*	B_2*	B_3*	B_4*	SD	SDg
Vinnytsia	0.760	0.259	0.179	0.185	0.434	0.371
Volyn	0.001	0.208	0.142	0.123	0.299	0.274
Dnipropetrovsk	0.621	0.369	0.356	0.485	0.540	0.531
Donetsk	0.387	0.083	0.096	0.532	0.385	0.246
Zhytomyr	0.639	0.228	0.158	0.164	0.392	0.312
Zakarpattia	0.459	0.173	0.088	0.095	0.445	0.344
Zaporizhzhia	0.696	0.303	0.212	0.568	0.514	0.471
Ivano-Frankivsk	0.523	0.175	0.127	0.235	0.378	0.324
Kyiv	0.465	0.253	0.335	0.124	0.507	0.465
Kirovohrad	0.751	0.230	0.144	0.123	0.467	0.380
Luhansk	0.412	0.000	0.000	0.039	0.198	0.000
Lviv	0.855	0,191	0.188	0.151	0.490	0.419
Mykolaiv	0.991	0.257	0.159	0.733	0.582	0.482
Odesa	0.790	0.166	0.176	0.124	0.465	0.361
Poltava	0.368	0.390	0.294	0.322	0.445	0.421
Rivne	0.489	0.181	0.116	0.202	0.388	0.310
Sumy	0.293	0.227	0.158	0.251	0.392	0.348
Ternopil	0.827	0.200	0.144	0.214	0.400	0.311
Kharkiv	0.428	0.149	0.167	0.114	0.424	0.330
Kherson	0.582	0.213	0.124	0.116	0.365	0.284
Khmelnytskyi	0.748	0.223	0.165	0.191	0.427	0.351
Cherkasy	0.689	0.247	0.160	0.145	0.406	0.321
Chernivtsi	0.541	0.150	0.091	0.076	0.357	0.239
Chernihiv	0.498	0.258	0.161	0.237	0.423	0.366
City of Kyiv	0.103	0.937	1.000	0.092	0.681	0.608

Notation for primary indicators: P_1 – GRP volume index, %; P_2 – stationary-source emissions, t/km^2; P_3 – GRP per capita, UAH; P_4 – unemployment, %; P_5 – disposable income per capita, UAH; P_6 – capital investment per capita, UAH; P_7 – foreign-trade intensity (exports + imports)/GRP, in original currency units per UAH million (for min-max normalization, the currency-conversion multiplier does not affect the normalized value); P_8 – export-to-import coverage ratio. N_1–N_8 are the corresponding normalized indicators. The P_2 and P_6 values in the matrix were reconstructed from the published B_1/B_3 and independently verified paired components; because B is rounded to 0.001, they represent a computational reconstruction rather than a replacement for the primary statistical table.

Source: compiled by the author.

values for individual economic or social characteristics while simultaneously exhibiting substantial gaps in other areas.

At the same time, the calculations presented here constitute an empirical test of the proposed methodology. The proxy indicators used for B_3 and B_4 do not fully capture natural capital and economic security, respectively. Future research should expand the indicator system to include natural-capital stocks, resource productivity, energy dependence, import concentration, diversification of external suppliers, and indicators of critical-infrastructure resilience.

The results provide a basis for moving from static interregional comparison to panel analysis and scenario modeling, in which a change in a specific management decision can be assessed by its simultaneous impact on all four balances.

PRACTICAL SIGNIFICANCE AND RECOMMENDATIONS

The proposed toolkit can be used by central government, regional authorities, and local governments when evaluating green-transformation programs.

The practical algorithm includes:

- defining the management decision and the territory to be assessed;
- selecting 1–3 statistically available indicators for each component of the four balances;

- defining a common comparison base and normalizing indicators;
- substantiating weights using equal, expert, or entropy-based approaches;
- calculating partial B_1–B_4 and integral *SD*;
- analyzing sensitivity to changes in weights and normalization parameters;
- comparing alternative scenarios and selecting a decision that prevents critical deterioration in any of the balances.

For practical policy, it is important to establish not only a target value for integral *SD* but also minimum acceptable thresholds for each B_j. This prevents a situation in which strong economic outcomes statistically compensate for an unacceptable deterioration in environmental security, social justice, or economic resilience.

CONCLUSIONS

The study substantiates a system of four basic balances of sustainable territorial development: "economic growth – environmental security", "economic efficiency – social justice", "current consumption – interests of future generations", and "economic openness – economic security". Combining them makes it possible to move from fragmented monitoring of indicators to analysis of trade-offs among competing objectives.

The methodological contribution consists in the proposed procedure for normalization, weight determination, calculation of partial and integral indices, geometric aggregation, and sensitivity analysis. The methodological refinement lies in distinguishing the level of simultaneous achievement of paired objectives B_j from the degree of their coherence $C_j = 1 - |X_j - Y_j|$, thereby giving the concept of "balance" a direct mathematical meaning and reducing the risk of interpreting a simple average as a measure of balance. A separate result is the parallel use of *SD* and *SDg* and the compensation gap $\Delta comp = SD - SDg$, which makes it possible to quantify the extent to which the integral result depends on stronger components compensating for weaker ones.

In practical terms, the model can be used to compare green-transformation scenarios, identify critical imbalances, and substantiate management decisions.

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ВПЛИВ ЕКОЛОГІЧНИХ РИЗИКІВ НА ОХОРОНУ ТА ЕКОНОМІЧНУ ДИФЕРЕНЦІАЦІЮ МІСЬКИХ ЗЕМЕЛЬ

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JEL: Q51; Q56; Q57

Гунько Л. А., Тітенко І. О. Вплив екологічних ризиків на охорону та економічну диференціацію міських земель

Сучасний розвиток міських територій відбувається в умовах посилення екологічних ризиків, серед яких особливого значення набувають забруднення ґрунтів, деградація земель, техногенне навантаження та наслідки кліматичних змін. Концентрація населення, виробничої інфраструктури та активізація будівельної діяльності зумовлюють зростання антропогенного навантаження на міські землі, що безпосередньо впливає на їх екологічний стан, функціональну придатність та економічну цінність. У зв'язку з цим особливої актуальності набуває проблема екологічного стану міських земель, яка дедалі більше визначає їхню економічну привабливість, інвестиційний потенціал і рівень вартості. Недостатня розробленість методичних засад комплексного врахування екологічних ризиків під час економічної диференціації міських земель зумовила необхідність дослідження взаємозв'язку між екологічним станом територій, режимом їх використання та економічною цінністю. Метою статті автори ставили дослідження екологічних ризиків міського землекористування, обґрунтування та оцінку їх впливу на процеси охорони міських територій та формування механізмів економічної диференціації вартості земель в умовах сучасного урбанізованого середовища в Україні. Під час дослідження було встановлено, що екологічні ризики (забруднення, близькість полігонів відходів, деградовані території, санітарно-захисні зони) безпосередньо впливають на зниження інвестиційної привабливості та ринкової вартості земель. Для мінімізації таких ризиків запропоновано підхід до врахування екологічних ризиків у системі економічного стимулювання міського землекористування. Визначено екологічні детермінанти вартості міських земель через поєднання показників транспортного навантаження, стану ґрунтів та рівня забезпеченості екосистемними послугами, які дозволяють перейти до кількісної оцінки землекористування. У статті обґрунтовано, що екологічна складова повинна бути інтегрована в механізми економічного стимулювання через: диференціацію платежів за землю, коригування нормативної грошової оцінки, формування тарифів у сфері поводження з відходами та врахування екологічної премії/дисконту при оцінці нерухомості. Такий підхід дозволяє перетворити